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(54) **Waveguide for an optical near-field microscope.**

(57) The waveguide comprises a transparent body (13) having a very sharp point at one end and being coated with a first opaque layer (14) such as metal. Said opaque layer (14) carries a layer (15) of an optically transparent material which, in turn, is covered by a second opaque layer (16). The apex of the point is removed so as to expose said transparent body (13) in a first aperture (18) and to expose said transparent layer (15) in a second aperture 17, said first aperture occupying an area below 0,01μm^2.

Light entering the transparent body (13) from its remote end is shone onto an object (4), the reflected light enters said second aperture (17) and is guided to a light detector (19) for further processing.

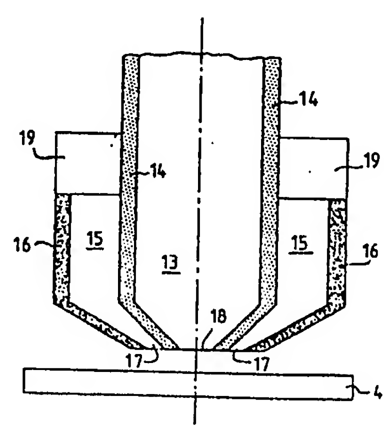


FIG. 2

WAVEGUIDE FOR AN OPTICAL NEAR-FIELD MICROSCOPE

This invention relates generally to the art of optical microscopy and in particular to the design of the objective aperture for an optical near-field scanning microscope.

Optical microscopes have a long history and their application has since long extended beyond research and the physician's practice. The search for viruses and bacteria as well as the manufacture of electronic circuits require microscopes of ever better resolution. The theoretical limit for the resolution of an optical microscope lies in the range of the wavelength of the light used, i.e. about 500 nm, since direct human inspection naturally requires visible light. The distance between two object points which an optical microscope can just resolve, when the illumination is incoherent and the microscope's aperture is circular, is $\sim 0{,}61\lambda/n \cdot \sin\theta$, wherein $n \cdot \sin\theta$ is the numerical aperture of the object lens, i.e. the product of the refractive index of the glass n and of the semi-angle θ of the cone of rays in the object space. Obviously, the numerical aperture should be large if a high resolving power is to be achieved (M. Born and E. Wolf, Principles of Optics, Pergamon Press, London 1959, p. 417f).

Numerous attempts to increase the resolving power of microscopes are known from the prior art. The most important achievements relative to the subject of the present invention have been disclosed in EP-A1-0112401 and EP-A1-0112402. The first-mentioned reference is directed to an optical near-field scanning microscope in which the "objective" consists of an optically trans-

parent crystal having a metal coating with an aperture at its tip, the diameter of the aperture being considerably smaller than one wavelength of the light used for illuminating the object.

The second-mentioned reference, EP-A1-0112402, concerns a light waveguide with an aperture the diameter of which is between 10 and 500 nm, and a method for manufacturing such a waveguide. This waveguide, too, consists of an optically transparent body which is coated with a multi-layer metal film.

The references cited above suggest the use of the objective either as an observing instrument looking at the object which is illuminated by some external light source, or inversely, the illumination is shone through the objective and the radiation reflected by the object is detected by a separate detector. While in both cases the purpose of increasing the resolution through reduction of the diameter of the objective is served, the disadvantages, however, are a very noisy picture on the one hand and a rather bulky apparatus on the other. It is an object of the present invention to teach an optical waveguide which overcomes these disadvantages while at the same time maintaining the narrowness of the aperture and the ease of manufacture.

Accordingly, the waveguide of the present invention comprises an optically transparent body having a fine point at one end thereof and being coated with a first opaque layer, with the characteristic that said first opaque layer is at least partly covered with a layer of an optically transparent medium which in turn is covered

with a second opaque layer, that the apex at the fine point of said transparent body including the opaque and transparent layers covering said body are removed, such that light entering the transparent body from the back can exit through an aperture at the point and be directed onto an object, and that light reflected by said object can enter said transparent layer through at least one aperture thereof and be guided to a light detector to which the transparent layer is optically connected.

Details of several embodiments of the invention will be described by way of example with the aid of the attached drawings in which:

Fig. 1 is a schematic representation of a conventional optical near-field scanning microscope;

Fig. 2 is a cross-section of one embodiment of the waveguide in accordance with the invention;

Figs.3 through 5 show embodiments of the waveguide with a square cross-section;

Figs.6 and 7 represent embodiments of a waveguide comprising optical fibers.

Fig. 1 shows the basic elements of an optical near-field scanning microscope as it is known from EP-A1-0112401. Briefly, a frame 1 is secured to a bench 2 which also carries a support 3 arranged for x/y movement of an object 4 to be inspected. An arm 5 of frame 1 carries a vertical adjustment appliance 6 for controlling the distance of an aperture 7 from object 4 with the

aid of a sensor 8. Attached to aperture 7 is an optical filter 9 which in turn is connected, via a light guide 10, to a photodetector 11. This arrangement assumes illumination of object 4 by an external light source, be it in reflection or transmission modes.

In an inverse arrangement, photodetector 11 would be replaced by a suitable light source, such as a laser, and the light reflected from the object would have to be collected by a separate light detector 12.

As mentioned before the present invention contemplates the integration of light source and detector in the vicinity of the object in order to reduce any disturbances that may be caused by the ambient light or stem from parts of the object other than that very part onto which the aperture is directed.

Referring to Fig. 2, an optically transparent body 13 is conventionally coated with an opaque layer 14. Body 13 may consist of a quartz crystal, for example, and carry a metal coating the thickness of which should be a few times the optical penetration depth, i.e. about $\lambda/10$ for visible light. Alternatively, body 13 may be the end of an optical fiber with the cladding removed. Body 13 should be pointed as sharply as possible, the radius of curvature of its tip being in the neighbourhood of 20 nm, for example. Methods to produce such sharply pointed transparent bodies are disclosed in EP-A1-0112402. An alternative method is ion milling.

Opaque layer 14 in itself may consist of a single coating of metal or o: a plurality of metal coatings, as

described in EP-A1-0112402, for better adhesion to the crystal or fiber material. Layer 14 carries a transparent layer 15 just thick enough to permit non-overdamped optical waveguiding, i.e. having a thickness on the order of $\lambda/2$, and tapered towards the apex to a thickness of about $\lambda/20$. A second opaque layer 16 is placed around transparent layer 15, and this may again consist of metal. The thickness of the second metal layer is not critical; it should be in the range of tenfold the penetration depth of the metal used. Of course, this layer may consist of several coatings of different metals, as in the case of layer 14. All of these layers 14 through 16 carried by body 13 can be produced by evaporation, sputtering, or other conventional thin film techniques.

Transparent layer 15 enclosed between opaque layers 14 and 16 forms a light waveguide for the radiation entering its annular aperture 17 after reflection by the object 4 of the rays exiting from a central aperture 18. The tapered shape of transparent layer 15 with a thickness below the wavelength of the light used favours the propagation of the reflected radiation in form of the TEM_{01} mode which has no sharp cutoff at subwavelength dimensions. (For the TEM_{01} mode cf. D. Pohl Operation of a Ruby Laser in the Purely Transverse Electric Mode TE_{01}, Appl. Phys. Lett., Vol. 20, No. 7, April 1, 1972, p. 266f.)

The waveguide 14, 15, 16 may be connected directly to a set of distributed photodetectors concentrically arranged around transparent body 13, or to an annular photodiode 19.

While Fig. 2 assumes a circular cross-section for

transparent body 13, which would particularly apply to an optical fiber, Figs. 3, 4 and 5 show a transparent body with a square cross-section. In Fig. 3, body 20 is partly covered with a transparent layer 21 over a metallization (not shown), the transparent layer 21 being tapered such that light entering through the four-sided aperture 22 is guided into a photodetector 23. The outer metallization of layer 21 is not shown for clarity of the figure.

Another embodiment is shown in Fig. 4 where the square body carries four independent waveguides 24, 25, 26, (waveguide 27 not shown) each ending in an individual photodetector 28, 29, 30 (photodetector 31 not shown). Light emitted from the central aperture 32 and reflected by the object enters into the four rectangular apertures 33 through 36 and is conducted, by the respective one of associated waveguides 24 through 27, to one of said photodetectors 28 through 31. This arrangement is particularly useful for differential microscopy by comparison of the output signals of oppositely located photodetectors.

Fig. 5 shows yet another embodiment with a transparent body 37 having a square cross-section. Light having exited through a central aperture 38 in the body after reflection by the object enters through apertures 39 and 40. The light waves propagating up wave guides 41, 42 are brought to interference at the joint 43 of waveguides 41 and 42. An electrooptic phase shifter 44 permits the adjustment of the relative phases of the arriving light waves. Joint 43 of the waveguides 41 and 42 preferably has a monomode cross-section. This arrangement provides differential phase information. In other words, it introduces phase contrast methods into optical near-field

scanning microscopy. To measure this phase contrast signal, a photodetector 45 is connected to joint 43.

In figures 6 and 7 implementations of the invention making use of glass fibers are shown. A glass rod 46 (Fig. 6) is connected to a light source (not shown) and emits light through an aperture 47. Rod 46 may be realized by a glass fiber. Attached to rod 46 is a glass fiber 48 with its end tapered to about $\lambda/20$ and metallized. Its aperture 49 receives the reflected light which is guided to a detector, not shown.

Fig. 7 is an arrangement with glass fibers in a configuration similar to the one shown in Fig. 4. Around a central glass rod or fiber 51 having an aperture 50 at one end, are arranged four receiving glass fibers 52 through 55 with their ends tapered to about $\lambda/20$ as explained in connection with Fig. 6 and defining apertures 56 through 59, respectively. This arrangement allows for differential reflectivity and differential phase contrast microscopy.

In the arrangements of Figs. 6 and 7, the spaces between the waveguides may be filled with a low-melting metal.

If the light source used to illuminate the object is chosen to be a laser, the man skilled in the art may elect to integrate the laser into the transparent body of Figs. 2 through 5. This can be easily done with a semiconductor laser in accordance with the teaching of EP-A1-0112402.

While the invention has been described in connection with an optical near-field scanning microscope, it will be self-evident for those skilled in the art that the waveguides in accordance with the invention can find application in connection with endoscopes used for the inspection of cavities, be it in living organisms or in natural or man-made devices and machines.

C L A I M S

1. Waveguide for an optical microscope, comprising an optically transparent body having a fine point at one end thereof and being coated with a first opaque layer, characterized in that said first opaque layer (14) is at least partly covered with a layer (15, 21, 26, 41, 42) of an optically transparent medium which in turn is covered with a second opaque layer (16), that the apex at the fine point of said transparent body (13, 20, 37) including the opaque and transparent layers (14, 15, 16, 21, 26, 41, 42) covering said body (13, 20, 37) are removed, such that light entering the transparent body (13, 20, 37) from the back can exit through an aperture (18, 32, 38) at the point and be directed onto an object (4), and that light reflected by said object (4) can enter said transparent layer (15, 21, 24...27, 41, 42) through at least one aperture (17, 22, 33...36, 39, 40) thereof and be guided to a light detector (19, 23, 28...31, 45) to which the transparent layer (15, 21, 24...27, 41, 42) is optically connected.

2. Waveguide for an optical microscope, comprising a first optically transparent body having a fine point at one end thereof and being coated with an opaque layer, characterized in that at least one second, pointed, optically transparent, opaque-coated body (48, 52...55) is arranged in juxtaposition with said first transparent body (46, 51), that the apices at the points of said transparent bodies (46, 48, 51...55), including their opaque coatings covering the points, are removed, such that light entering said first transparent body (46, 51) from the back can exit through an aperture (47, 50) at

the point and be directed onto an object (4), and that light reflected by said object (4) can enter said second, pointed, optically transparent, opaque-coated body (48, 52...55) and be guided to an associated light detector.

3. Waveguide in accordance with claim 3, characterized in that the optically transparent layer (15, 21, 24...27, 41, 42) is tapered towards its aperture (17, 22, 33...36, 39, 40) to a thickness of about one twentieth of the wavelength of the light used.

4. Waveguide in accordance with claim 2, characterized in that the second transparent body (48, 52...55) is tapered towards its aperture (49, 56...59) to about one twentieth of the wavelength of the light used.

5. Waveguide in accordance with claim 1, characterized in that said transparent body (20) has a rectangular cross-section and is partly covered with a transparent layer (21) on top of said first opaque layer, the transparent layer (21) being bevelled such that a light wave entering through its aperture (22) is guided to a single light detector (23) connected to said transparent layer (21).

6. Waveguide in accordance with claim 1, characterized in that the sides of said transparent body (20) are provided with two or more light guides (24...27), each of which being connected to an associated light detector (28...31) at one end, and at the other forming apertures (33...36) arranged about the aperture (32) of the trans-

parent body (20) in a symmetrical configuration.

7. Waveguide in accordance with claim 6, characterized in that the transparent body (20) has a square cross-section, and that four light guides (24...27) end in apertures arranged in a cross-like configuration.

8. Waveguide in accordance with claim 1, characterized in that said transparent layer (15) is optically connected to a circular light detector (19).

9. Waveguide in accordance with claim 1, characterized in that said transparent body (37) on opposite sides, on top of its opaque layer, carries a pair of light guides (41, 42) connected in a joint (43) leading to a light detector (45), one of said light guides (41) being provided with an optical phase shifter (44).

10. Waveguide in accordance with claim 8, characterized in that said light guides (41, 42) have apertures (39, 40) respectively situated on both sides of the aperture (38) of said transparent body (37).

11. Waveguide in accordance with claim 2, characterized in that said first transparent body (46, 51) and said second transparent body (48) or bodies (52...55) are surrounded by an opaque material, namely low-melting metal.

12. Waveguide in accordance with claim 2, characterized in that said first transparent body (46, 51) and/or the second transparent body (48) or bodies (52...55) consist of glass fibers.

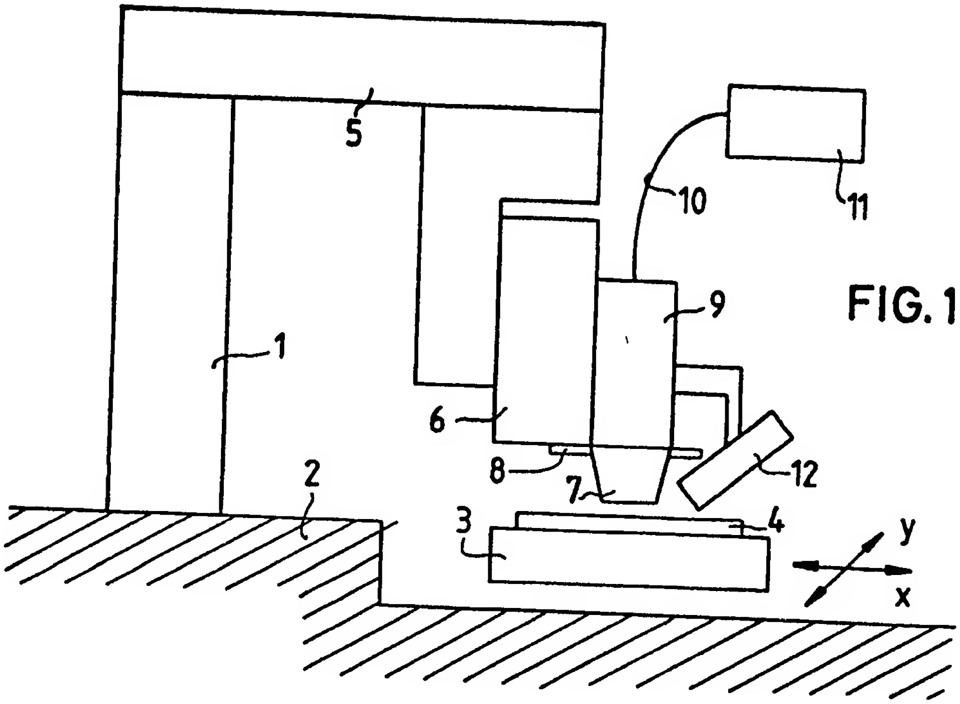


FIG. 1

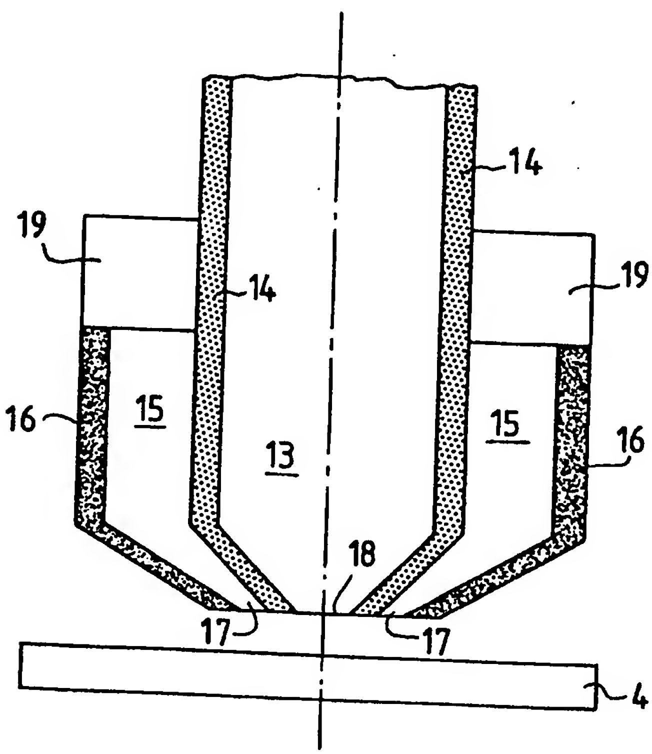


FIG. 2

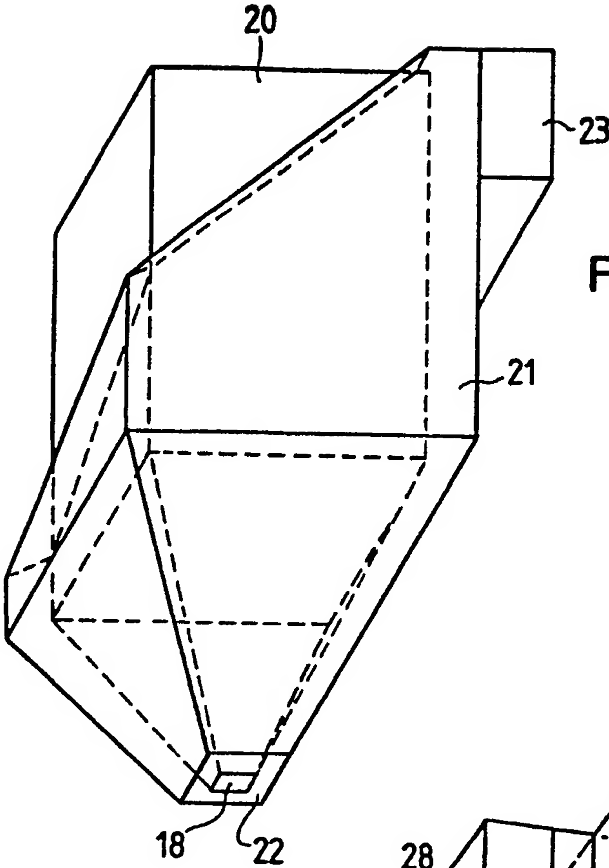


FIG. 3

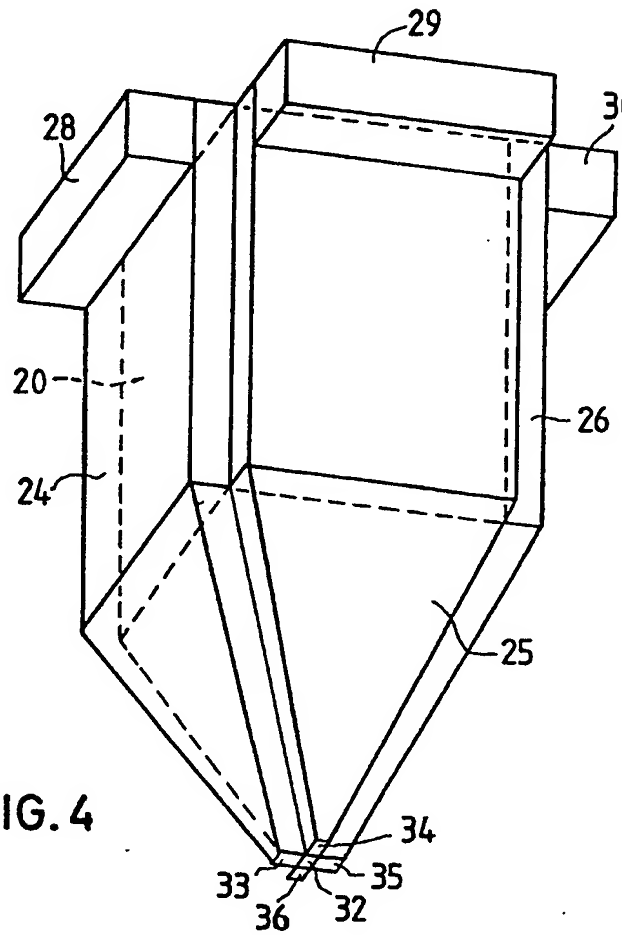


FIG. 4

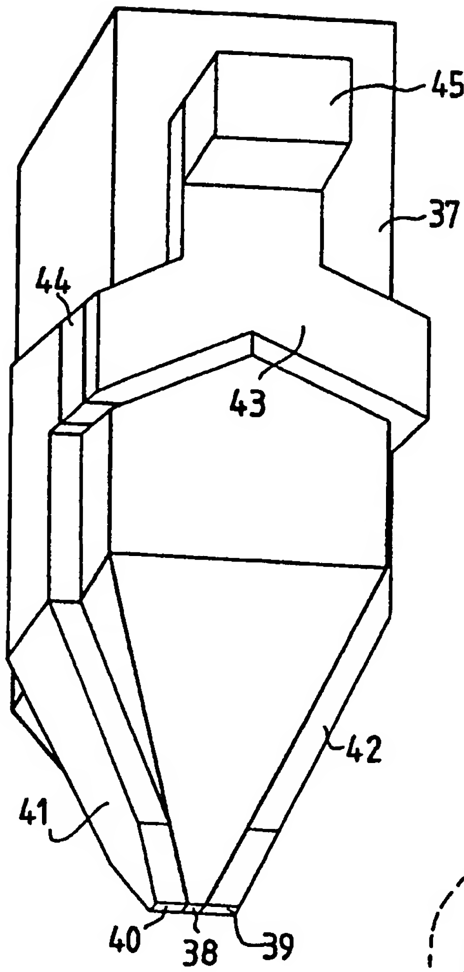
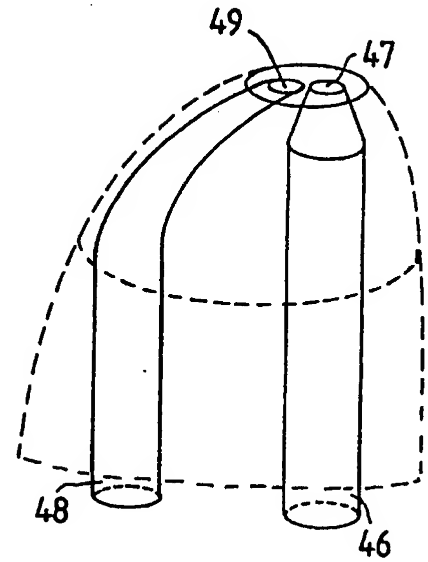


FIG. 5

FIG. 6



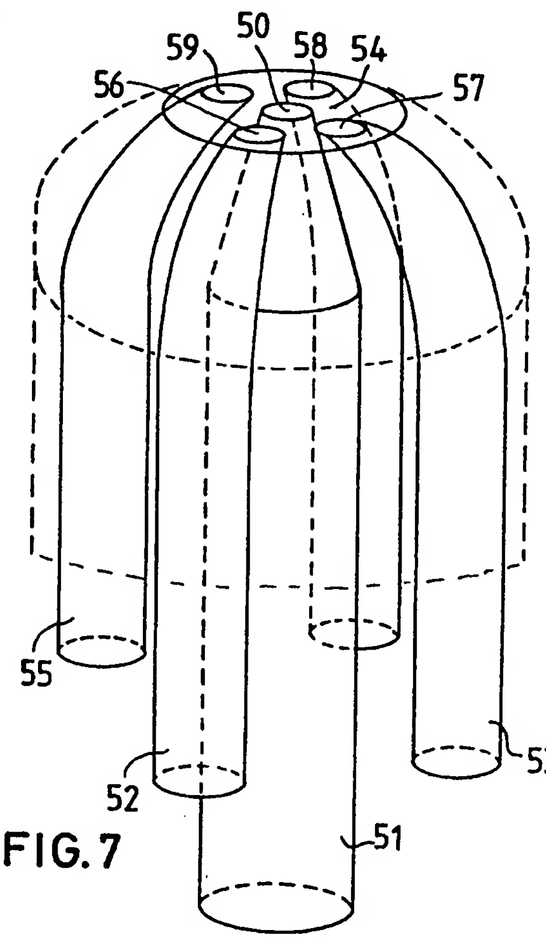


FIG. 7

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EUROPEAN SEARCH REPORT

0185782

Application number

EP 84 11 5848

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl 4)
D,A	EP-A-0 112 401 (IBM) * Claim 1 * ---	1,2	G 02 B 21/00
A	US-A-3 809 893 (B.W. DOBRAS) * Column 3, lines 6-15 * ---	1,2	
A	DE-A-3 243 890 (THE SECRETARY OF STATE FOR DEFENCE) * Claim 2 * ---		
A	US-A-3 905 852 (K. MUKAI et al.) * Figure 3a; abstract * -----		

TECHNICAL FIELDS SEARCHED (Int. Cl 4)

G 02 B 21/00
G 02 B 27/58
G 06 K 7/10

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	10-07-1985	FUCHS R

CATEGORY OF CITED DOCUMENTS

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